Hard X-ray polarization measured with a Compton polarimeter at synchrotron radiation facility

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Abstract

A hard X-ray polarimeter with CdTe detectors has been developed for measurement of the degree of X-ray polarization at synchrotron radiation facilities. It utilizes 90° Compton scattering from the low Z targets. Measurements were performed at both facilities of the beamline BL38B1 in SPring-8 and the beamline BL14A in KEK-PF. The degrees of X-ray polarization for 20 keV X-rays are 99% and 82% at the BL38B1 in SPring-8 and BL14A in KEK-PF, respectively. The polarization degrees in the energy range of 15 and 40 keV correspond to 99.6 ± 0.2% and 96.1 ± 0.2% at the beamline BL38B1 in SPring-8. The analyzing power of the polarimeter was estimated by the Monte Carlo simulation with EGS4. The synchrotron radiation facilities provide highly polarized X-ray beams at energies above 15 keV.

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1. Introduction

Hard X-ray observation at energies above 10 keV is crucial to the investigation of nonthermal emission from celestial X-ray sources. Polarimetry of the nonthermal X-rays provides a new method for the study of the structure of the accretion disk around black hole (BH) candidates and AGN, the magnetic fields of SNR and Blazer, and the emission mechanism of a γ-ray burst. The latest development of the high-throughput hard X-ray mirror allows X-ray imaging observation with higher orders of magnitude sensitivity, compared with coded mask telescopes in the energy range of 20–40 keV [1,2]. In addition, the hard X-ray telescope can also be highly effective for observations of X-ray polarization because of the large...
effective area and the low background property. Hence, an X-ray polarimeter, as a focal-plane-imaging detector that can be combined with the X-ray telescope, is strongly required.

To satisfy this requirement, we have been developing two types of X-ray polarimeters based on X-ray photo-absorption [3] and Compton scattering [4]. In order to evaluate their performance as a cosmic hard X-ray polarimeter, it is necessary to calibrate the polarimeter with a highly polarized, well-monochromatized, and well-collimated X-ray beam. X-ray beams in a synchrotron facility can fulfill all these requirements and therefore are very reliable for the evaluation of the X-ray polarimeter. Therefore, we have been using the facility for the calibration and development of the cosmic hard X-ray polarimeter.

For the evaluation of the performance of every polarimeter proposed for hard X-ray astronomy, the knowledge of the beam-line polarization degree is critical because the analyzing power of the polarimeter should be calibrated using the known degree of linear polarization [5]. Hence, a compact hard X-ray polarimeter being easy to operate, such as the one described in the following sections, is necessary for the calibration because it is important to check the beam-line polarization degree before the experiment regarding the performance of proposed cosmic X-ray polarimeters using the beam-line.

The degree of polarization for the X-ray beam is usually measured by utilizing the dependence of Bragg reflection in a crystal. However, since the energy of the reflected photon depends on the crystal lattice spacing, the measured X-ray energy is less than 10 keV and the energy band is very narrow (100 eV). Hence, this Bragg reflection polarimeter is not suitable for the measurement of X-ray polarization for the continuum hard X-ray region.

An X-ray polarimeter employing Compton scattering is reliable and suitable for measuring the degree of polarization for the hard X-ray beam in the synchrotron radiation facility. Therefore, we have developed a compact Compton hard X-ray polarimeter with a scattering target and CdTe detectors. In this paper, we describe the design and performance of the Compton hard X-ray polarimeter, and the measured degree of linear polarization in the energy range of 15–40 keV at the beamline BL38B1 in SPring-8 and the beamline BL14A in KEK-PF.

2. Experimental setup

2.1. Compton scattering polarimeter

Fig. 1 shows the Compton scattering polarimeter used to measure the polarization degree of the X-ray beam at synchrotron radiation facilities. It consists of two cadmium telluride (CdTe) detectors and a target attached to an acrylic rotating table. The two CdTe detectors (Amptec XR-100T-CdTe) are mounted perpendicular to each other viewing the target at a scattering angle $\theta \sim 90^\circ$. Each detector has an effective area of $3 \text{ mm} \times 3 \text{ mm}$ and thickness of 1 mm. Employment of the two detectors assures the investigation of any systematic error caused by cylindrical asymmetry.
inhomogeneous distribution in the material, and position misalignment. The distance between the centre of the target and the surface of the detector can be varied from 30 to 200 mm. The choice of distance depends on the priority of the experimental observation such as quick observation of the beam polarization or close investigation of the linear polarization for the spin-dependent X-ray absorption spectroscopy. Both the CdTe detectors and the target are rotated along the azimuth angle by a rotating table. An acryl pipe of 200 mm length holds the target on the central axis of the table. The target material can be exchanged on the pipe. Here, we used a target made of polypropylene. The long distance of 200 mm from the table to the target is sufficient to prevent the scattered photons from impinging on the table. The X-ray transmitted through the target can also be used to monitor the beam intensity.

2.2. Experimental arrangement for the measurement of polarization

Fig. 2 shows the typical experimental arrangement used for the measurement of the polarization degree of X-rays at the synchrotron radiation facility. The incidence direction of X-rays is along the Z-axis. The energies of incident X-ray beams were monochromatized by the Si double-crystal monochromator. Incident X-rays through a slit of size 100 μm × 100 μm were scattered by a polypropylene target located at the origin in the X–Y–Z coordinates. The polypropylene target was 10 mm in diameter and 10 mm in length. The X-ray beam was passed through a pipe filled with He gas before incidence on the target in order to avoid additional air scattering. The distance from the centre of the target to the CdTe detector was 150 mm. The scattered X-rays at a scattering angle \( \theta = 90 \pm 0.8^\circ \) were detected by the detectors located in the X–Y plane. By rotating the two CdTe detectors along the \( \varphi \)-direction with a 15° step, we measured the angular modulation of the scattered X-rays. The pulse height of the individual output signals from each of the CdTe detectors was analysed with a peak hold ADC, and the data were accumulated event-by-event through a CAMAC bus in a personal computer.

The channel number of the ADC was calibrated with standard X-ray sources of \(^{55}\)Fe (5.9 keV), \(^{109}\)Cd (22.1 keV), and \(^{241}\)Am (59.5 keV). The flux of the incident X-ray beam was calibrated by detecting the transmitted X-rays from the target with a 1-mm-thick YAP scintillation counter behind a 300 μm Cu filter, which is located downstream of the target. The count rate of the YAP scintillation counter was measured using a discriminator and CAMAC scalar.

3. Results and discussion

3.1. Measurement of the degree of X-ray polarization

Using the concise Compton scattering polarimeter, the X-ray polarization was measured at two synchrotron radiation facilities, the beamline
of BL38B1 in SPring-8 and that of BL14A in KEK-PF. Although the electric vectors of the incident X-rays are horizontal at the beamline BL38B1 in SPring-8 and vertical at the beamline BL14A in KEK-PF, respectively, this polarimeter can measure the X-ray polarization without any change of the experimental setup regardless of the electric vector of the X-ray.

For the incident X-ray energy of 20 keV at the beamline BL38B1 in SPring-8, Figs. 3(a) and (b) show the pulse height spectra of scattering photons at the azimuth angles $\phi$ of 90° and 0°, respectively. The spectral shapes at the beamline BL14A in KEK-PF were also similar. In the spectrum at azimuth angle of 90°, two peaks were clearly observed and the energies of the first and the second one were 19.2 and 20.0 keV, respectively. These values correspond to the energies of Compton scattering at the scattering angle of $\theta \approx 90°$ and Rayleigh scattering, respectively. The broad spectrum at azimuth angle of 0° indicates the occurrence of multiple scattering events in the target, because the background rate was negligible (<0.2%) at all the azimuth angles for the run performed without the target.

Figs. 4(a) and (b) show the azimuth angle distributions of the scattered photons from 20 keV polarized X-rays at both the synchrotron radiation facilities, respectively. The distribution is shown as the ratio of the count of the CdTe detector to that of the YAP scintillation counter for each angle. The count of CdTe detector is the sum of the counts for all channels greater than 10 keV in the energy range used for all of the measurements. It is clearly observed that both the angular distributions of the scattered X-rays are highly modulated in the direction of the linear polarization of the incident X-rays. According to the Compton and Rayleigh scattering cross-sections, the modulation curve is expressed by the following equation:

$$N(\phi) = A + B \cos^2(\phi - \phi_0)$$  \hspace{1cm} (1)

where $\phi$ is the azimuth angle and $\phi_0$ is the initial phase angle. $A$ and $B$ are a constant and the amplitude of the modulation, respectively, and they are derived from the fitting of the angular distribution to Eq. (1) with a least-squares method.

We define the modulation parameter $M$ for a degree of linear polarization $P$ as

$$M(P) = \frac{N_{\text{max}} - N_{\text{min}}}{N_{\text{max}} + N_{\text{min}}} = \frac{B}{2A + B}$$ \hspace{1cm} (2)

At the 20 keV X-rays, the modulation parameters are 0.926 ± 0.002 and 0.768 ± 0.002 for the beamline BL38B1 in SPring-8 and the BL14A in KEK-PF, respectively. The statistical errors are those of the least-squares fitting. Using the modulation parameter $M$, the degree of linear polarization $P$ is
given by

\[ P = \frac{M(P)}{M(P = 1)} \]  

where \( M(P = 1) \) is the modulation parameter when the degree of polarization is 100\% in the X-ray beam. It is the so-called analysing power.

In order to obtain the \( M(P = 1) \) for the 20 keV X-ray beam, we employed the Monte Carlo calculation using EGS4 code. As it takes into account the photon linear polarization, multiple scattering and the Doppler broadening of the Compton-scattered photons, the estimation of \( M(P = 1) \) is reliable compared with analytical calculation \([6,7]\). In Figs. 5(a) and (b), the simulated energy spectra for 20 keV X-ray are shown at the azimuth angles of 90° and 0°, respectively. The energy spectrum was smeared by a Gaussian function so as to take into account the energy resolution of the CdTe detector. It is clear that these energy spectra show good agreement with the experimental ones shown in Fig. 3. The simulated modulation curve is also shown in Fig. 5(c). For the 20 keV X-ray with 100\% polarization, the analysing power \( M(P = 1) \) of 0.940 is obtained. From the analysing power \( M(P = 1) \) and the modulation parameter \( M \), the polarization for the synchrotron radiation facilities are determined to be 0.986 ± 0.002 for the beamline BL38B1 in SPring-8 and 0.817 ± 0.002 for the BL14A in KEK-PF, respectively. The result for the beamline BL38B1 in SPring-8 is the first calibration data of the degree of polarization in the hard X-ray region. The result for the beamline BL14A in KEK-PF is consistent with the degree of 0.80 ± 0.05, which was measured at the neighbouring beamline BL14C with a vertical wiggler \([8]\).

3.2. Measurements of dependence of the degree of polarization on X-ray energies

The dependence of the degree of X-ray polarization on the X-ray energies was investigated in the beamline BL38B1 at SPring-8 facility. The incident X-ray beams were monochromatized by a Si(511) double-crystal monochromator in the energy range from 15 to 40 keV with a 5 keV step, corresponding to the Bragg angle \( \theta_B \) from 23.3° to 8.54°, respectively. We applied a smaller polypropylene target, 5 mm in diameter and 7 mm in length, to the X-ray polarimeter. By applying the smaller target, we obtained a 1.03 times greater analysing power than when using the target 10 mm in diameter and 10 mm in length. Figs. 6(a) and (b) show the azimuth angle distribution of the scattered photons for the 20 and 40 keV polarized X-rays, respectively. The measured polarization degree is 0.984 ± 0.002 for 20 keV X-rays beam. It is consistent with the result obtained with the target 10 mm in diameter and 10 mm in length,
taking the analysing power into account. The DC component of the modulation at 40 keV X-rays was slightly greater than that at 20 keV X-rays. In

Fig. 6. Azimuth angle distribution from a polypropylene target for (a) 20 keV photons and (b) 40 keV photons scattered by $\theta \approx 90^\circ$ from a polypropylene target at (a) the azimuth angle of $90^\circ$ and at (b) that of $0^\circ$ (c) calculated azimuth angle distribution of 100% polarized 20 keV X-rays scattered by $\theta \approx 90^\circ$ from a polypropylene target.

Fig. 5. Pulse height spectra obtained by Monte Carlo calculation with EGS4 for 100% polarized 20 keV photons scattered by $\theta \approx 90^\circ$ from a polypropylene target at (a) the azimuth angle of $90^\circ$ and at (b) that of $0^\circ$ (c) calculated azimuth angle distribution of 100% polarized 20 keV X-rays scattered by $\theta \approx 90^\circ$ from a polypropylene target.

Fig. 7, the dependence of linear polarization on X-ray energy is shown together with the modulation parameter $M$ and the analysing power $M (P = 1)$. The average polarization degree is estimated to be $0.978 \pm 0.013$ in the energy range of 15 and 40 keV. The modulation parameters in the energy range between 15 and 40 keV gradually degraded from 0.958 to 0.923, although the analysing power $M (P = 1)$ was almost constant in the energy range. Consequently, the degree of polarization of the incident X-ray beam is slightly decreased from $0.996 \pm 0.002$ to $0.961 \pm 0.002$ with increasing photon energy from 15 to 40 keV. Since the effect of additional polarization provided by the reflection in the Bragg monochromator is at most 0.4% for all of the measurements, it is
inferred that the dependence arises from an error in alignment to the synchrotron orbit plane.

4. Conclusion

We have developed a hard X-ray polarimeter with CdTe detectors to measure the degree of X-ray polarization at synchrotron radiation facilities. Measurements were performed at both facilities of SPring-8 and KEK-PF. The beamline BL38B1 at the SPring-8 provides a highly polarized X-ray beam in the energy range between 15 and 40 keV. The facilities have been used for the calibration of various kinds of hard X-ray polarimeters for astrophysical applications. In particular, the present work was preliminary to the calibration of two types of hard X-ray polarimeters that we are developing for astrophysical applications and that have already been calibrated at the synchrotron facilities [4,9].

References